Symmetry and Network Connectivity in Transmission Switching

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Outline

Introduction

Symmetry in UC & TS

Anti-Islanding in Transmission Switching

Before we start ...

Solving UC and TS problems:

Problem Formulation $\rightarrow$ Black Box Commercial Solvers

Strategy: Improve formulations.

- Pro: Improving formulations can dramatically improve solution times.
- Con: There are restrictions on what can be efficiently modeled.

- Pro: Commercial software is very good, and is continually getting better.
- Con: Commercial software focuses more on general methods. Problem specific methods me more effective

Before we start ...

Solving UC and TS problems:

Problem Formulation $\rightarrow$ Commercial Solvers Adapted To Our Problems

Strategy: Improve formulations **and** algorithms.

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Two Examples of Advances in Optimization Methods

- Tailor general advances in optimization to specific problems.
  - Symmetry-breaking and the unit commitment (UC) and transmission switching (TS) problems.
- Adapt algorithms to allow for better modeling techniques.
  - Enforce anti-islanding constraints in TS problem.

Outline

Symmetry in Optimization

- Integer programming software has recently implemented symmetry-breaking techniques.
  - Version 10.0 in CPLEX
  - Version 3.0 in Gurobi
- These general techniques have led to significant gains in computational efficiency.
  - Gurobi: “25% geometric speedup on the whole [test] set”
- Does symmetry matter in TS and UC? If so, can we do better than general techniques?

Symmetry in The Unit Commitment Problem

$$
\begin{array}{c|cc}
\text{Time} & \text{Gen 1} & \text{Gen 2} \\
\begin{array}{c}1\\2\\3\\4\\5\\6\\7\\8\\9\\10\end{array} &
\multicolumn{2}{c}{\begin{pmatrix} 1 & 0 \\ 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 0 & 1 \\ 0 & 1 \\ 0 & 1 \\ 1 & 1 \\ 1 & 0 \\ 1 & 0 \end{pmatrix}}
\end{array}
$$

On/Off status of Generators 1 & 2

- Ignoring transmission, if generators 1 and 2 are identical, permuting their schedules will give an equivalent solution.
- Permutations schedules between identical generators are symmetries.
- Having many identical solutions can make the problem difficult.

Symmetry in The Unit Commitment Problem

$$
\begin{array}{c|cc}
\text{Time} & \text{Gen 1} & \text{Gen 2} \\
\hline
1 & 0 & 1 \\
2 & 1 & 1 \\
3 & 1 & 1 \\
4 & 1 & 1 \\
5 & 1 & 0 \\
6 & 1 & 0 \\
7 & 1 & 0 \\
8 & 1 & 1 \\
9 & 0 & 1 \\
10 & 0 & 1
\end{array}
$$

On/Off status of
Generators 1 & 2

- Ignoring transmission, if generators 1 and 2 are identical, permuting their schedules will give an equivalent solution.
- Permutations schedules between identical generators are symmetries.
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Symmetry in RTS-96

- Symmetry exists when there are identical generators at the same bus in the UC problem.
- When transmission constraints are ignored, they exist whenever identical generators are present in the model.
- RTS-96 is an IEEE test network with 73 buses and 96 generators.
  - Only 9 different types of generators- lots of symmetry when transmission is ignored
  - With transmission, there is still a lot of symmetry.
    6 “U50” generators at bus 122
    5 “U12” generators at bus 115
    3 “U100” generators at bus 107...

Symmetry in Unit Commitment

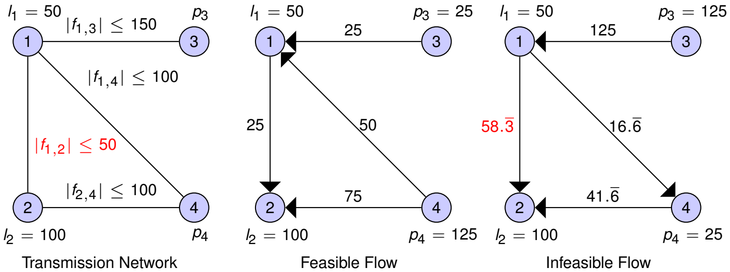
Number of Generators	CPLEX Default (s)	Modified Symmetry (s)
21	544.0	57.9
23	386.5	78.9
23	1227.6	308.6
24	1169.3	155.7
26	978.4	138.4
26	529.5	68.4
26	558.4	107.4
26	425.6	74.4
26	465.3	111.4
26	1320.9	104.0
27	535.3	105.4
27	594.3	1339.8
28	679.5	307.7
28	444.0	107.8
29	975.6	1400
30	1514.6	631.0
30	862.7	381.8
31	1210.3	1197.4
31	783.5	107.3
31	712.5	296.1
31	1360.8	220.7
34	739.0	1401.9
35	1204.9	404.5
37	2808.2	447.0
42	1540.1	396.8

- Computational results show that specialized symmetry breaking can improve overall solution times in the UC problem.
- We extended this work to TS problems with identical transmission lines
  - We saw a 50% decrease in time needed for 1-hour RTS-96 instance.
- Can we exploit the structure of the UC problem further?

From *Symmetry in Scheduling Problems*, Ostrowski et al.

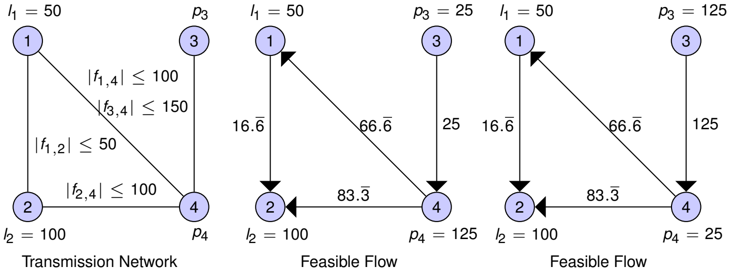
Generator Location and Symmetry

- Generators at different locations are not necessarily symmetric.
- Permuting production output between two generators may not give an equivalent solution:



Symmetry Not Broken by Transmission

- Sometimes, location does not break symmetry, i.e. production schedules between two identical generators can be permuted.



- How likely is this to exist?

Finding Symmetry with Transmission Constraints

- By studying the properties of the network, a lot more symmetry can be found (this symmetry will not be found by current versions of CPLEX and Gurobi).
- We studied the Illinois power network trying to identify identical generators in the transmission problem. This problem contains more than 200 generators and the transmission network contains around 2,000 buses.

	Sets of Identical Generators						
	2	3	4	5	6	8	12
Same Location	8	1	2	1	0	0	0
Same Location and Adjoining Buses	28	6	10	2	1	3	1

Recognizing this additional symmetry reduces computation time of 24-hour UC problem by 25%.

Outline

Introduction

Symmetry in UC & TS

Anti-Islanding in Transmission Switching

Islanding

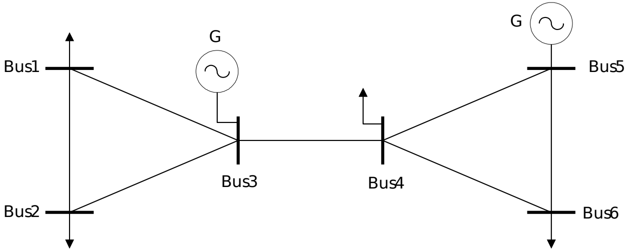
Islanding in Power Systems

- Islanding in power systems is usually a result of equipment failure.
- An outage occurring in a line may unintentionally disconnect the network and create islands. Resulting islands may contain a disproportionate amount of generation or load.

Islanding in Transmission Switching

- Islanding resulting from TS is different, because it is not a response to equipment failure.
- Each island generated by the TS problem will be load-balanced.
- The problem, however, is to synchronize the system when islands are reconnected.

Islands Caused by TS



- Solving the TS problem over this network may give a solution that switches the line connecting buses 3 and 4.
- Disconnecting this line will contain islands.

Formulating Anti-Islanding Constraints

- Let $z_k(t)$ be the binary variable representing if transmission line k is switched or not.
- Let F be a set of transmission lines such that if all lines in F were turned off, the transmission network would be disconnected.
- The constraints

$$\sum_{f \in F} z_f(t) \geq 1 \ \forall t \in T$$

  ensure that all lines in F are not removed.
- Let $\mathcal{F}$ be the set containing all such sets F.
- The constraints

$$\sum_{f \in F} z_f(t) \geq 1 \ \forall F \in \mathcal{F}, \ \ \forall t \in T$$

  ensure there are no islands in the network.

How Many Anti-Islanding Constraints?

RTS-96 System	# of Constraints with $\lvert F \rvert =$ 1	2	3	4
Total Constraints	2	163	159	442,933

- We generate a subset of anti-islanding constraints for the RTS-96 test case. There are almost 500,000 sets of transmission lines containing at most 4 lines that, when switched, create islands.
- Adding constraints for every set will make the problem impossible to solve.
- We need to find another way to enforce network connectivity. We do this by modifying the branching algorithm using callback functions in the software.

Traditional Branch and Bound

- Solve the LP relaxation of a subproblem.
- If solution is integer, the subproblem is solved.
- If not, choose a fractional variable x_i that should be integer.
- Create one new subproblem with $x_i = 0$ and another with $x_i = 1$.

Modified Branch and Bound

- Solve the LP relaxation of a subproblem.
- If solution is integer, the subproblem is solved.
- If not, choose fractional variable x_i that should be integer.
- **If x_i represents the switched status of a transmission line i:**
  - **Look at the network formed by switching line i.**
  - **Find the set C of all lines that would create islands if they were switched.**
- Create one new subproblem with $\{x_i = 0$ **and $\mathbf{x_j} = \mathbf{1}$ for all $\mathbf{c} \in \mathbf{C}$**$\}$ and another with $x_i = 1$.

Note: The set C can be found in linear time.

Results

- We tested the proposed algorithm on a RTS-96 instance.
- Using our algorithm, the anti-island TS problem actually solved faster than the basic TS problem. This is because that branching process is able to fix more variables.

	Time Required to Solve 1-Hour TS(s)	
	TS	Anti-Islanding TS
RTS-96	95.1	23.9

- The algorithm can easily be extended to enforce anti-islanding in contingency analysis when transmission line outages are modeled.

Conclusion

- Commercial solvers are very effective at solving integer programming problems.
- However, there are opportunities to improve solution times by adapting general integer programming techniques to exploit the structure of the UC / TS problem.

Questions?

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